# International Collaboration on $CO_2$ Sequestration

Annual Report

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## Disclaimer

## Abstract

The objective during this reporting period was to begin a two-year sub-task to update an assessment of environmental impacts from direct ocean sequestration. The approach is based on the work of Auerbach et al. (1997) and Caulfield et al. (1997) to assess acute impacts, but uses updated information concerning injection scenarios and bioassays.

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## Executive Summary

This reporting period covers the first half of the two-year sub-task, which includes a review of recent and ongoing engineering studies concerning practical modes for the ocean discharge of $CO_2$, review of recent and ongoing experimental studies concerning the rates (and extent) of formation and dissolution for $CO_2$ hydrates, review of recent and ongoing biological studies concerning organism response to reduced pH and increased $CO_2$ concentration, and the definition of discharge scenarios. These steps have been successfully completed. Results-to-date were presented at the Annual Fall Meeting of AGU (December 2005) and will be presented at the Annual DOE Meeting on Carbon Capture and Sequestration (May, 2006).

## Background

In 1996 MIT conducted a study for DOE/FE on the Environmental Impacts of Ocean Disposal of $CO_2$ (Adams and Herzog, 1996). Among other things, we compiled available data on acute impacts of lowered pH on marine organisms. At the time, most data were from laboratory studies in which coastal (near surface) fauna were subjected to constant pH for fixed durations. We modified existing plume models to describe the spatial pH distributions resulting from various discharge scenarios (falling dry ice cubes, rising liquid droplets released either as fixed point sources or from a pipe towed by a moving ship, dense gravity currents created from $CO_2$-enriched seawater, and deep lakes). A probabilistic exposure model was then used to convert the spatial pH distributions into time-varying levels of pH that would be experienced by passive organisms moving through the respective plumes. In the process, a new approach was developed to utilize the constant concentration data from laboratory assays to evaluate acute impacts from time-varying field exposures (Auerbach et al., 1997; Caulfield et al., 1997).

The current sub-task involves up-dating this assessment with more recent data, and extending the assessment to consider longer term exposure to smaller levels of stress which could result in ecosystem effects.

## Results and Discussion

We have been reviewing the literature regarding three aspects of the assessment: 1) exposure studies that report the effects on marine organisms of exposure to elevated $CO_2$ levels (and also ways to relate these often idealized exposure studies to potential impact from real-world $CO_2$ injections), 2) identification of practical scenarios for discharging $CO_2$ to the ocean with maximum dilution, and models for assessing this dilution, and 3) measurement of rates (and extent) of formation and dissolution of negatively buoyant forms of $CO_2$ (especially hydrates). This review has lead to the selection of three scenarios to be evaluated in detail. Our review is summarized briefly below.

***Exposure Studies:*** Since publication of our two papers, newer biological studies have been reported, including Barry and Seibel (2003), Kita, et al. (2003), Portner, et al. (2004), Seibel and Walsh (2001), Tamburri et al. (2002), Shirayama (2002), and Watanabe, et al.

(2003), IPCC (2005), and Barry et al. (2005). In general, these have improved on earlier studies by focusing on elevated $CO_2$ as well as depressed pH as stressors, and by studying animals acclimated to higher pressures and lower temperatures more representative of the intermediate and deep ocean depths into which CO2 might potentially be released. Some researchers have also adopted a similar approach for integrating constant exposure data with time-varying exposures (Sato, 2002).

***Discharge Studies:*** A number of new computer models have been developed to analyze pH and $CO_2$ perturbations from ocean discharge of $CO_2$. Many stem from our earlier international collaboration on $CO_2$ sequestration project (Alendal and Drange, 2001; Sato and Sato, 2002; Chen et al., 2003; Wannamaker and Adams, 2006). There is also recognition that the most relevant times scales of environmental impact might be on the order of days, corresponding to distances of kilometers to 10s of kilometers downstream from the discharge (Israelsson, 2003), hence demanding that predictions of $CO_2$ and pH be extended to these distances.

Meanwhile, current thinking has changed regarding the types of discharge scenarios that would be most practical/least harmful. For example, few people are talking about dry ice (because of its high energy costs), or dense gravity currents (because of their high $CO_2$ concentration, and hence expected impact). However there continues to be interest in droplet and particle plumes that can attain high initial dilution in intermediate depth waters, especially if dispensed from a moving ship or from a long bottom-mounted diffuser; and deep lakes (or hydrated $CO_2$ buried in surficial marine sediments) that would achieve moderate periods of isolation, followed by large ultimate dilution in deep ocean waters. Plus there has been strong interest in clever ways to create negatively buoyant forms of $CO_2$ (other than dry ice) that sink, leading to greater dilution and longer sequestration; these forms include solid $CO_2$ hydrates, hydrate composites (combinations of liquid $CO_2$, hydrates and seawater); very cold liquid $CO_2$; and $CO_2$ combined with $CaCO_3$ as a slurry or an emulsion (Wannamaker and Adams, 2006).

***Process Studies:*** Data on $CO_2$ hydrate dissolution and settling rates have been reported in field studies by Rehder et al. (2004) and laboratory studies by Warzinski et al. (2002). Riestenberg et al. (2005) have observed the rates of settling and diameter shrinkage of cylindrical hydrate composite particles in field studies off of Monterey, California.

***Scenario Selection:*** Based on the above review, we have selected three discharge scenarios for detailed evaluation: a hydrate plume released from a stationary ship/platform, hydrate particles released from a moving ship, and a liquid droplet plume discharged from a long, bottom-mounted manifold.

## Conclusion

Using computer models summarized in Adams and Wannamaker (2005), we have evaluated the volumes of impacted water as a function of pH for the $CO_2$ released from a 500 MW coal-fired plant using each of the discharge scenarios. See Figure 1.

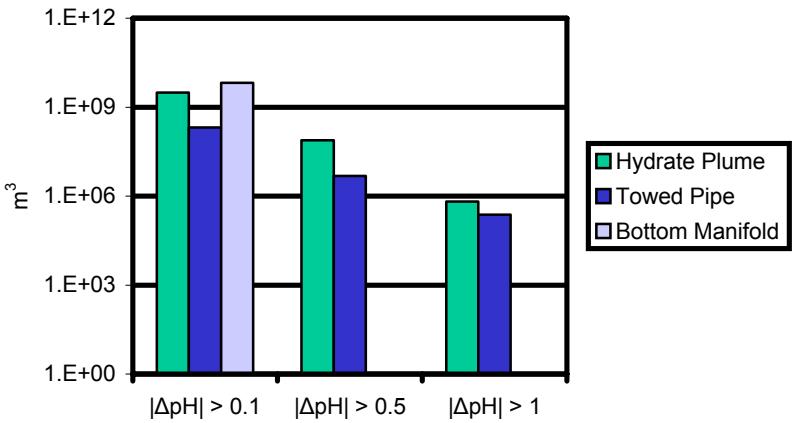


**Figure 1. Ocean volumes impacted by $CO_2$ from a single 500 MW coal plant**

The change of pH that organisms within a fixed zoogeographic region can experience without any ecosystem effect is likely on the order of 0.1 (IPCC, 2005; Barry et al., 2005). This seemingly strict standard would still allow about 400 GTC to be dispersed uniformly in the ocean below a depth of 1000 m. This represents about 8000 500 MW coal plants of the type considered above. Figure 2 shows the fraction of the world oceans that would experience an absolute pH change of more than 0.1 units, as a function of time, assuming 4000 such plants discharging over a period of 50 years.

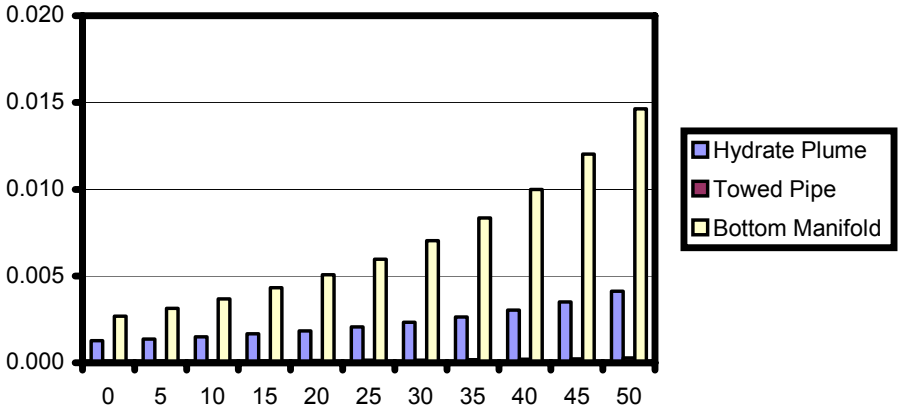


**Figure 2. Percent of ocean volume below 1000m having an absolute pH change greater than 0.1 units versus time in years, assuming 4000 single-plant discharges.**

These results were presented in at the Fall 2005 Meeting of AGU (Barry et al., 2005) and will be presented in revised form at the Annual DOE Meeting on Carbon Capture and Sequestration (May, 2006).

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